DEVELOPMENT AND BEAM TESTS OF AN AUTOMATIC ALGORITHM FOR ALIGNMENT OF LHC COLLIMATORS WITH EMBEDDED BPMs*

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Abstract

Collimators with embedded Beam Position Monitor (BPM) buttons will be installed in the LHC during the upcoming long shutdown period. During the subsequent operation, the BPMs will allow the collimator jaws to be kept centered around the beam trajectory. In this manner, the best possible beam cleaning efficiency and machine protection can be provided at unprecedented higher beam energies and intensities. A collimator alignment algorithm is proposed to center the jaws automatically around the beam. The algorithm is based on successive approximation, as the BPM measurements are affected by non-linearities, which vary with the distance between opposite buttons, as well as the difference between the beam and the jaw centers. The successful test results, as well as some considerations for eventual operation in the LHC are also presented.

INTRODUCTION

The LHC is a high-energy circular collider located at CERN. It is designed to accelerate 3.23×10^{14} protons in two counter-rotating beams to achieve collisions in the experimental insertions at a center-of-mass energy of 14 TeV. A beam cleaning or collimation system is in place to intercept potentially dangerous beam halo particles before they are deposited in the super-conducting magnets or other sensitive areas of the machine [1]. A total of 108 collimators are installed, mainly in IR3 and IR7 for momentum and betatron offset cleaning respectively.

An LHC collimator is made up of two blocks (jaws) of graphite, tungsten or copper material, which are positioned on either side of the beam in parallel to the beam trajectory. The extremities of each jaw, known as corners, can be moved independently by dedicated stepping motors. Each jaw is classified as 'left' or 'right', depending on its location with respect to the beam axis. The upstream jaw corners are those which see the incoming beam, while the downstream corners see the beam exiting the collimator.

The collimator jaws are opened to various gaps, forming a four-stage hierarchy to be able to clean with the maximum efficiency. The correct positions are achieved only if the beam centers and beam sizes at the collimator locations are known precisely. A beam-based alignment procedure has been adopted at the LHC during the 2010-2012 runs [2], in which these parameters are determined by moving inwards the jaws on either side of the beam until a beam loss spike is detected on a Beam Loss Monitor (BLM).

A faster alignment and online monitoring of the local beam position can be achieved if BPMs are embedded in the collimator jaws [4]. This new design envisages the installation of two BPM button pick-ups per jaw, with one positioned in each jaw corner. The pick-up buttons in the jaw corners are installed in a tapered region, with a retraction of around 10 mm from the active surface of the jaw, and are hence protected from possible direct beam impacts.

A horizontal prototype collimator equipped with embedded BPMs was installed in the SPS in January 2010. A number of beam tests have been performed in the past couple of years to verify the alignment accuracy and compare the results achieved to those of the BLM-based technique [5].

BPM DATA ACQUISITION

The BPM button pick-up signals are processed by electronics based on compensated diode detectors optimized for high-resolution. Two diode orbit front-end prototypes were built and tested in the laboratory and with beam [6]. In this novel technique, the diode detectors convert the short beam pulses into slowly varying signals, which are sent to a multi-channel analogue-to-digital converter (ADC). The ADC samples are averaged and sent as User Datagram Protocol network packets by a built-in microcontroller in the SPS tunnel to an intermediate server. Data from the left-up (LU), right-up (RU), left-down (LD) and right-down (RD) BPM electrodes are included in the packet payload.

The server forwards the packets on request to the collimator application running in the CERN Control Center. This is an ad hoc setup conceived to allow maximum flexibility for changing top-level control software and parameters during the beam tests.

BPM-BASED ALIGNMENT ALGORITHM

Neglecting non-linearities in the BPM measurements, the beam center C can be calculated as follows [7]:

$$C = \frac{J_L - J_R + 2x_{bpm}}{4} \times \frac{V_L - V_R}{V_L + V_R} \quad (1)$$

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where J_L and J_R are the left and right jaw positions, x_{bpm} is the retraction of the button pick-ups with respect to the jaw surface, and V_L and V_R are the signals from the button pick-ups on the left and right jaws respectively. The objective of the alignment is to minimize C in Eq. (1). A successive approximation algorithm was developed to automatically align the collimator jaws around the beam center from any starting jaw gap and beam offset. A flowchart of the algorithm is shown in Fig. 1. The first step is to estimate what would be the aligned position for the jaw furthest from the beam, J_i:

$$J_i = C + J_{i-1} \tag{2}$$

where i is an iterator over the successive approximation steps required due to non-linearities, J_{i-1} is the current jaw position, and C is the beam center measured by the BPMs. Once the jaw is reaches the supposedly aligned position, a new estimate is obtained for the beam center using Eq. (1). The loop has two terminating conditions. The first is when the measured beam center is below the error which can be specified as an input parameter: $|C| \leq C_{error}$. The second is when the jaw gap decreases below a minimum gap: $G \leq G_{min}$. This is done to ensure that the jaws do not inadvertently scrape away the beam during the alignment procedure. If $G = G_{min}$, the algorithm attempts to continue the alignment by moving the jaw closest to the beam outwards, rather than the jaw farthest from the beam inwards.

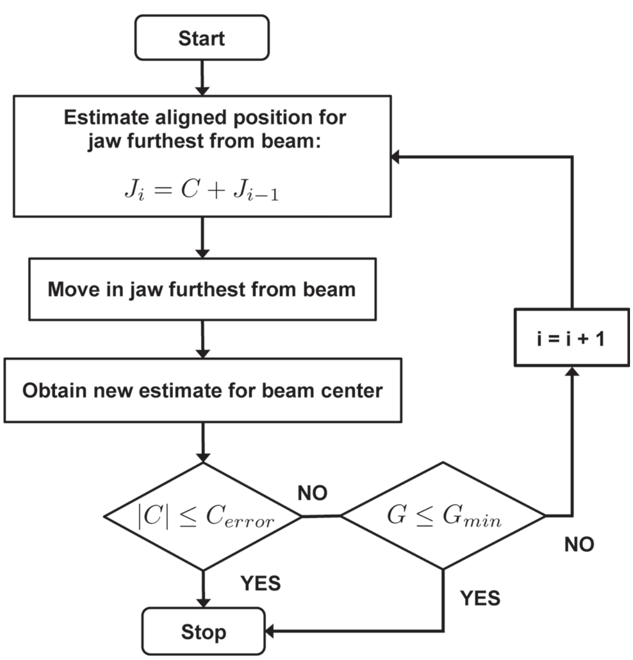

Figure 1: Flowchart of the BPM-based successive approximation alignment algorithm.

RESULTS

Alignment trials were conducted with circulating beam at an energy of 270 GeV. One LHC-type bunch with an injection intensity of 1.2×10^{11} p was circulating in the SPS.

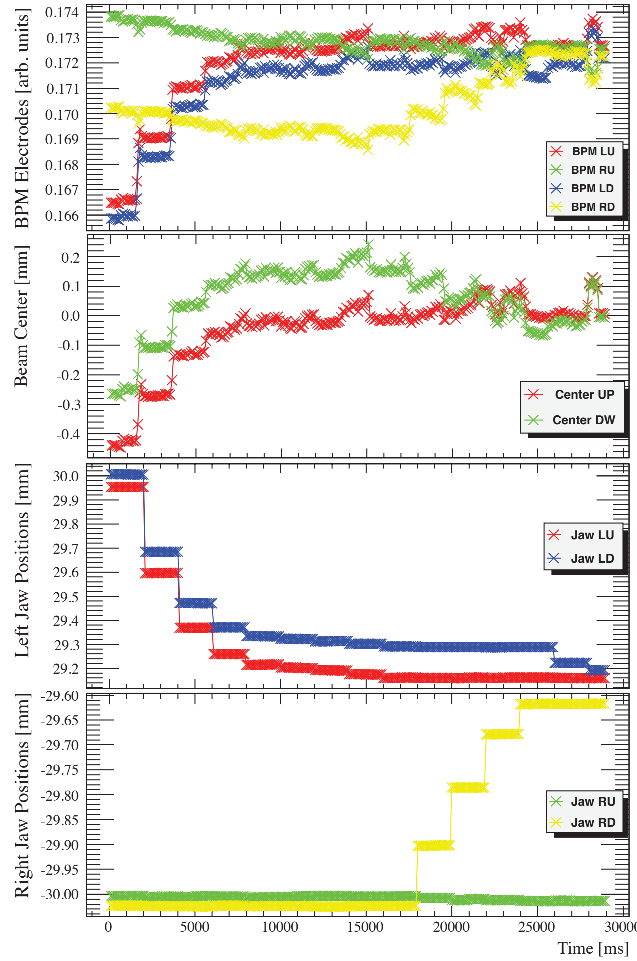

Figure 2: Raw electrode signals, measured beam center and collimator jaw corner positions during a typical automatic alignment in the SPS.

The alignment parameters were changed for each alignment, and are listed in Table 1. Two types of starting jaw positions were considered. In the first case, the jaws are initially set at parking positions around the zero position. In the second case, the jaws are initially positioned off-center, with $|C| > 3.5$ mm. The alignment time is strongly influenced by the time interval and the alignment accuracy required, and initial jaw gap to a lesser degree, as the BPM non-linearities are proportional to the jaw gap. The shortest alignment time achieved was of ~20 s, a factor 6 improvement over the best achieved alignment time of ~120 s with the BLM-based technique. The collimator jaw corner positions, raw electrode signals and measured beam center during a typical automatic alignment are shown in Fig. 2. Approximately 11 and 4 steps are required with the left and right jaws respectively until they are finally aligned after 30 s.

The BPMs are positioned in the SPS prototype collimator to measure the beam offset in the horizontal plane. Vertical beam offsets could affect the measurements due to non-linearities. Hence, a test was conducted to verify the extent of the measurement errors. The first step was to position the jaws symmetrically around the beam us-

Table 1: Alignment parameters and the corresponding alignment times achieved.

Parameter	Alignment Trials									
	1	2	3	4	5	6	7	8	9	10
Step Interval [s]	5	2	2	5	1	2	1	1	1	1
Accuracy [μm]	5	1	5	5	5	1	10	5	1	1
Initial Jaw Gap [mm]	50	60	60	48	35	35	35	21	21	35.5
Initial Jaw Center [mm]	0.00	0.00	0.00	6.00	7.50	7.50	-7.50	-3.50	4.50	12.25
Final Jaw Gap [mm]	35.93	43.15	58.50	35.37	19.93	19.65	20.45	13.90	11.39	10.44
Alignment Time [s]	47	105	29	81	17	52	23	26	24	34

ing the automatic BPM-based alignment algorithm. Then, vertical orbit bumps of $+2.5$ mm followed by -2.5 mm were introduced at the collimator location. The change in the measured BPM electrodes and the corresponding shift in the measured beam centers (taking into account a collimator jaw gap of 20 mm) are shown in Fig. 3. A minor shift of $\sim$50 μm was detected, which is negligible for operational purposes considering the magnitude of the orbit bump introduced. The effect in the downstream corner BPM electrode signals is more evident for the negative orbit bump, and vice-versa for the positive orbit bump, as the orbit bump cannot be applied at the same longitudinal position in both cases.

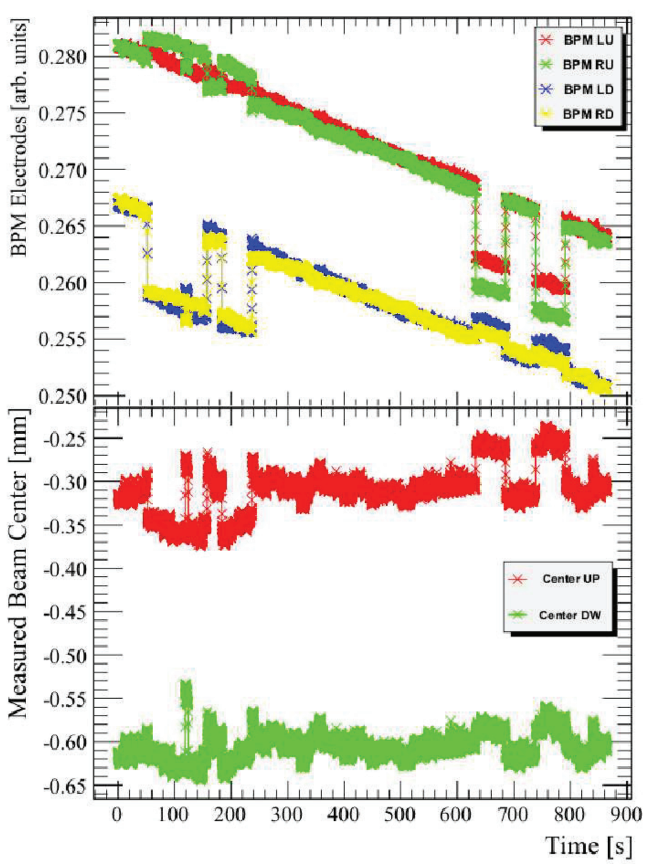

Figure 3: Changes in the measured BPM electrode signals and the calculated beam center due to vertical orbit bumps of $+2.5$ mm (100-300 s, ON-OFF-ON) and -2.5 mm (650-850 s, ON-OFF-ON).

CONCLUSION

Collimators with embedded BPMs will be installed in the LHC to monitor the beam position at the collimator locations with greater precision. An algorithm for automatically centering the jaws around the beam, based on feedback from the BPM readouts, was described. Results from tests with a prototype collimator in the SPS were presented, where an alignment time of $\sim$20 s was reached with an accuracy of 5 μm. The algorithm will be used for collimator alignment in the LHC, where the BPMs could allow for fill-to-fill alignments and also be integrated into the LHC beam orbit feedback system. This would provide a gain in time of almost one hour (an improvement of two orders of magnitude) when compared to alignments held during the 2012 LHC run.

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